Feedback and Formation of Massive Star Clusters in Giant Molecular Clouds

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Abstract. It is well known that the energy input from massive stars dominates the thermal and mechanical heating of typical regions in the interstellar medium of galaxies. These effects are amplified tremendously in the immediate environment of young massive star clusters, which may contain thousands of O and B stars. We present models of star cluster formation that attempt to account for the interplay between feedback and self-gravity in forming clusters, with application to systems ranging from the Orion Nebula Cluster, the Galactic Center clusters like the Arches, and super star clusters.

1. The Initial Conditions for Galactic Star Cluster Formation

Star formation in disk galaxies appears to be dominated by a clustered mode (Lada & Lada 2003), occurring in regions of the disk that are gravitationally unstable (Martin & Kennicutt 2001). The most unstable mass scales are about $1.3 \times 10^7 (\sigma_{\rm gas}/6\ {\rm km\,s^{-1}})^4 (\Sigma_{\rm gas}/10\ M_\odot {\rm pc^{-2}})^{-1} M_\odot$, roughly consistent with the observed cutoff of the Galactic Giant Molecular Cloud (GMC) mass function (Williams & McKee 1997). GMCs are gravitationally bound (Solomon et al. 1987), and there is a comparable amount of atomic gas associated with these structures (Blitz 1990). Altogether, a significant fraction ($\sim 1/2$) of the total gas mass inside the solar circle is organized into bound structures.

The lifetimes of GMCs are not well known. Blitz & Shu (1980) used observational and theoretical arguments to infer a GMC lifetime of a few times 10^7 yr; their argument based on photoevaporation of the clouds was confirmed in a more extensive calculation by Williams & McKee (1997). The rocket effect associated with the photoevaporation displaces the molecular gas from regions of active star formation at the same time the gas is being transformed from molecular form to atomic and ionized form. Leisawitz, Bash & Thaddeus (1989) found that open star clusters older than about ~ 10 Myr were not associated with molecular clouds, which is consistent either with post-star-formation cloud lifetimes shorter than this age or with relative velocities of star clusters and their parent clouds of about $10\,{\rm km\,s^{-1}}$. Elmegreen (2000) presented a number of arguments for star formation to occur in about $1-2$ dynamical timescales, particularly from the small age spreads in clusters such as the Orion Nebula Cluster and from the statistics of the presence of young stars in regions of dense gas. Hartmann (2003) has argued for such rapid star formation in Taurus. On the other hand, the observation that the angular momentum vectors of GMCs in M33 are small and are both pro- and retro-grade (Rosolowsky et al. 2003) may

indicate a relatively long lifetime so that angular momentum can be shed by magnetic braking (e.g., Mestel 1985) and/or cloud-cloud collisions in a shearing disk (Tan 2000).

Most star formation in GMCs is concentrated in *clumps* that occupy a relatively small fraction of the volume and have a small fraction of the mass. Within clumps are over-dense regions that we refer to as *cores* that form individual stars or binaries (Williams, Blitz, & McKee 2000). Star-forming clumps are identified by H_2O masers, outflows, and far infrared and radio continuum emission (Plume et al. 1997; Hunter et al. 2000; Sridharan et al. 2002; Beuther et al. 2002; Zhang et al. 2002; Mueller et al. 2002; Shirley et al. 2003). Most of the 350 μm emission maps of Shirley et al. (2003) have morphologies consistent with quasi-spherical, virialized distributions. Typical properties of clumps are masses $M \sim 100 - 10^4\,M_\odot$, diameters ~ 1 pc and surface densities $\Sigma \sim 1\,\mathrm{g\,cm^{-2}}$.

Clump properties are very similar to those of the smaller infrared dark clouds (IRDCs) (Carey et al. 1998), which are dense, cold regions embedded in GMCs. Thus, understanding the origin of IRDCs is crucial for progress in the fields of both star cluster formation and galaxy formation and evolution. Carey et al. noted nongaussian emission line profiles of H_2CO from 9 out of 10 IRDCs. This may indicate short formation timescales via a triggering mechanism. IRDC morphologies are also more filamentary than the sub-mm emission maps of star-forming clumps, which suggest that the latter represent a more evolved stage.

Possible triggers for IRDC formation include compression of parts of GMCs (which are likely to contain clumpy substructure) by shock waves driven by cloud-cloud collisions (Scoville, Sanders & Clemens 1986; Tan 2000), spiral density waves (Sleath & Alexander 1996), ionization fronts (Elmegreen & Lada 1977; Thompson et al. 2004), supernovae (e.g. Palous, Tenorio-Tagle & Franco 1994) or stellar winds (e.g. Whitworth & Francis 2002). Clumps that were previously pressure-confined and gravitationally stable may suddenly become unstable. The contraction of the cloud can be halted by the onset of star formation (McKee 1989). We expect that the protocluster will come into an approximate equilibrium in which pressure support balances self-gravity. Some pieces of evidence in support of this view are the approximately spherical morphologies of star-forming clumps (Shirley et al. 2003); the timescales of star cluster formation estimated from outflow momentum generation rates (Tan & McKee 2002); and the empirical age spreads of stars in young clusters, such as the Orion Nebula Cluster (Palla & Stahler 1999), which are quite long compared to the dynamical or free-fall timescales of clumps, $\bar{t}_{\rm ff} = (3\pi/32G\bar{\rho})^{1/2} = 1.0 \times 10^5 (M/4000 M_\odot)^{1/4}\Sigma^{-3/4}$ yr. This last point requires comment, since Elmegreen (2000) uses the Orion Nebula Cluster as an example of star formation on a dynamical time. He estimated the density in the cluster prior to star formation as $n_{\rm H} = 1.2\times10^5\ \mathrm{cm^{-3}}$, corresponding to a free-fall time of 1.25×10^5 yr. If the star formation occurred over a time $t_{\rm sf} = 10^6$ yr, then $\eta \equiv t_{\rm sf}/\bar{t}_{\rm ff} \simeq 8 \gg 1$. He used the dynamical time $t_{\rm dyn} \equiv R/\sigma$ to compare with $t_{\rm sf}$. If the virial parameter $\alpha_{\rm vir} \equiv 5\sigma^2 R/GM \sim 1$, as observed in star-forming regions (McKee & Tan 2003), then $R/\sigma = 2.0\bar{t}_{\rm ff}/\alpha_{\rm vir}^{1/2} \simeq 2.5\times10^5$ yr. For $t_{\rm sf} \simeq 10^6$ yr, star formation in the Orion Nebula Cluster was rapid, but not so rapid that a quasi-equilibrium treatment is invalid.

2. Pressurized Star and Star Cluster Formation

McKee & Tan (2002; 2003) considered star formation from marginally unstable, turbulent gas cores that are embedded in high pressure regions, such as the centers of star-forming clumps where $P \simeq 1.8G\Sigma^2 = 8.5 \times 10^9 \Sigma^2 \mathrm{K\ cm^{-3}}$. High pressures cause equilibrium cores to be compact, $r_{\rm core} \simeq 0.06(m_{*f}/30M_\odot)^{1/2}\Sigma^{-1/2}\mathrm{pc}$, and collapse times short, $t_{*f} \simeq 1.3 \times 10^5 (m_{*f}/30M_\odot)^{1/4}\Sigma^{-3/4}$ yr, where m_{*f} is the final stellar mass forming from the core with 50% efficiency. These properties help to overcome some objections to core-based models of massive star formation (Stahler, Palla & Ho 2000; Tan 2003). The model helps to understand features of the Orion hot core (Tan 2004), a close example of a massive protostar.

We have applied the above *turbulent core* star formation model to star clusters (Tan & McKee 2002). As a first approximation we assume that stars form independently from one another. This ignores the effects of mutual stellar interactions (e.g. Ostriker 1994; Elmegreen & Shadmehri 2003; Bonnell, Bate & Vine 2003). The simplicity of our approach means we only need to specify a stellar initial mass function (IMF) and an overall star formation rate to define a particular star cluster formation model. We use an empirical IMF in the form of a Salpeter power law ($d\mathcal{N}/d\ln m \propto m^{-1.35}$) at the high-mass end. We parameterize the star-formation rate in terms of $\eta \equiv t_{\rm sf}/\bar{t}_{\rm ff}$, the number of free-fall timescales it takes to form the stars. We adopt a star-formation efficiency of 0.5. Stars are drawn at random from the IMF according to this rate and their individual protostellar evolution is followed. The properties of all the individual stars, such as bolometric and ionizing luminosities and protostellar outflow momentum flux, are summed up to give the overall cluster properties. The effects of discreteness of the IMF are easily probed via Monte Carlo simulations of many star clusters.

These models were used to estimate the expected protostellar outflow momentum flux from forming clusters as a function of the star formation rate. Most models of outflows (e.g. Königl & Pudritz 2000; Shu et al. 2000) predict a linear relation between the accretion and outflow rates from protostars. The outflow velocity is of order the escape speed from the stellar surface. From a comparison to a sample of observed cluster outflows we estimated that $\eta \sim 10$, but with large uncertainties (Tan & McKee 2002).

3. Feedback Processes in Star Cluster Formation

Feedback processes that act against gravitational collapse and accretion of gas to protostars include radiation pressure (transmitted primarily via dust grains), thermal pressure of ionized regions and ram pressure from stellar winds, particularly MHD-driven outflows from protostars that are still actively accreting. Pressure support from turbulent bulk motions of the gas and the turbulent magnetic field is likely to be quite important in the initial clump (McKee & Tan 2003). Indeed the decay of this turbulence may be one of the most important factors controlling the onset of star cluster formation (McKee 1989). Forming stars in the protocluster can rejuvenate the turbulence, primarily by the momentum input from their MHD outflows.

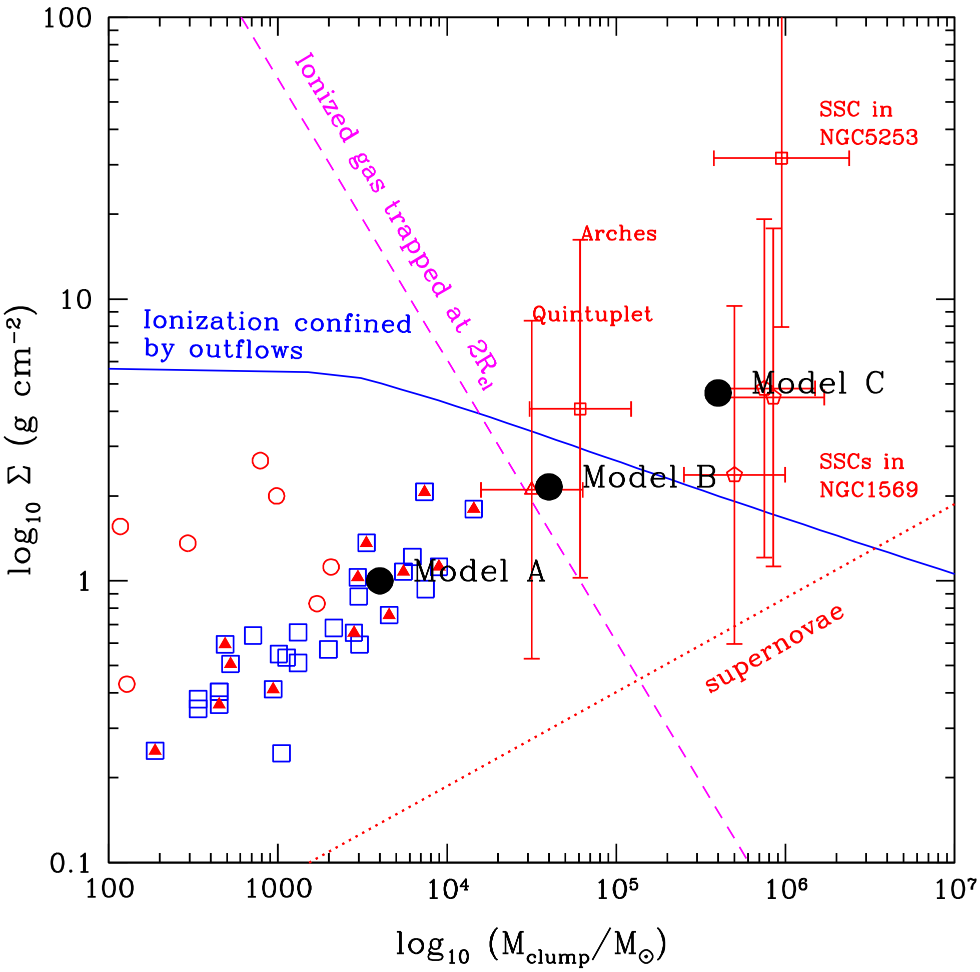

Figure 1. Surface Density vs. Mass diagram for star cluster formation. To the right of the dashed line the escape velocity from twice the clump radius is greater than the ionized gas sound speed ($\sim 10\,\mathrm{km\,s^{-1}}$) and ionizing feedback is less effective. The dotted line (of constant volume density) shows when the formation time, $\eta\bar{t}_{\rm ff}$, equals 3 Myr, assuming $\eta = 10$. Below this line supernova feedback becomes important. Above the solid line, ionizing photons from a typical sampling of the stellar IMF are confined by a protocluster wind formed from the combination of individual protostellar outflows (Tan 2001), again assuming $\eta = 10$. The open circles are the outflow sample used in Tan & McKee (2002), the open squares are the sample of Mueller et al. (2002), with solid triangles indicating presence of an HII region. The Arches and Quintuplet Galactic center clusters and several SSCs are shown, including corrections for formation efficiency. The solid circles are theoretical feedback models (Tan & McKee 2001 and shown in Fig. 3b).

Tidal torques among cores and their formation from a turbulent medium lead to a distribution of initial angular momenta. This distribution and the effectiveness of transport processes may also be important in regulating the

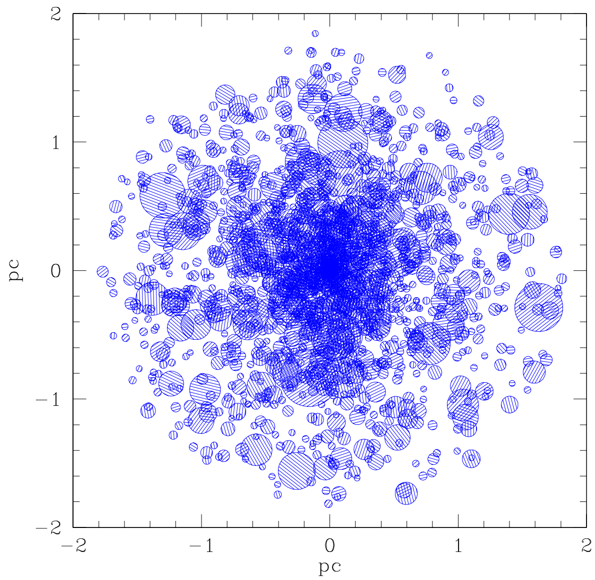

Figure 2. Projected initial density structure of proto-SSC medium (model C), consisting of cores embedded in an intercore medium (not shown).

cluster star formation rate. Important transport processes include magnetic braking (Mestel 1985; Allen, Li & Shu 2003), the magneto-rotational (Balbus & Hawley 1991; Salmeron & Wardle 2003) and gravitational instabilities (Larson 1984; Johnson & Gammie 2003) in disks, including global modes such as spiral density waves (Lynden-Bell & Kalnajs 1972) that may be easily induced by the presence of binaries or massive planets (Blondin 2000). We shall assume that these processes are efficient enough not to impede stellar accretion.

The complexity of the feedback processes and their interplay with a turbulent, self-gravitating medium forces us to make several simplifying assumptions in our modeling. Our goal is to explore which processes and aspects of the problem are most important. First we layout the parameter space of cluster mass and surface density (Fig. 1). As described in the caption, we can make simple estimates of when various feedback effects are important: e.g. the dashed line indicates when the escape speed from twice the protocluster radius is the ionized gas sound speed. Using the adopted empirical value for the overall star formation rate of $\eta = 10$, we show the condition for star formation to be complete within 3 Myr (i.e. before supernova feedback is important). With this rate we can also estimate the combined properties of a protocluster wind composed of superposed MHD outflows. This wind can be dense enough to confine ionizing feedback. Various observed star clusters are also shown in Fig. 1.

To move beyond these simple estimates we have constructed a dynamical feedback model (Tan & McKee 2001). The key element here is to investigate the effect of a turbulent and clumpy medium. We approximate this structure by dividing the gas into a population of cores with 80% of the total mass and an intercore medium. The cores have a mass spectrum $d\mathcal{N}/d\ln m \propto m^{-0.6}$, a uniform density, and a centrally concentrated initial spatial distribution (Fig. 2). The dynamics of the cores are affected by the potential of the overall protocluster and feedback effects from a stellar population at the cluster center. These include

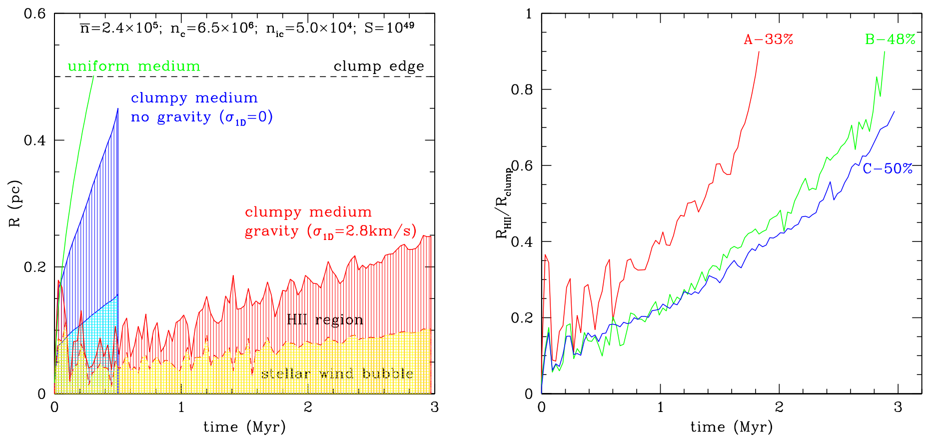

Figure 3. Evolution of feedback in protoclusters. (a) Left panel: test case showing size evolution of the HII region and stellar wind bubble created by a single O star with ionizing photon luminosity $S = 10^{49}\ \mathrm{s}^{-1}$ embedded in a typical Galactic protocluster (model A), with mean, core and intercore densities indicated in units of $\mathrm{H\,cm^{-3}}$. In a uniform medium at the mean density the HII region expands to the clump edge in just over 10^5 yr. If the medium is clumpy the feedback progresses more slowly because ionization fronts tend to encounter much denser gas with short recombination times and inner cores shield outer regions. In this modeling we treat the HII region and wind bubble in one dimension, averaging over angular variations. The thermal pressure of the HII region confines the ram pressure of the stellar wind bubble, which is shown by the inner shaded region. Break-out occurs after about 6×10^5 yr. Finally, including self-gravity so that the cores have turbulent motions and the protocluster is in virial equilibrium, feedback is severely confined for at least 3 Myr. It is harder to push the cores out of the potential of the clump and their motions lead to the continuous replenishment of neutral gas in the HII region. (b) Right panel: evolution of HII region size for clumpy, self-gravitating models A, B and C for protoclusters, forming with $\eta = 30$. The final star formation efficiency of each model is shown, assuming formation stops once the HII region reaches the edge of the clump or after 3 Myr by the action of supernovae. Non-supernova feedback is quite weak in models B and C and the embedded phase lasts several Myr.

radiation pressure, stellar winds and ionization, which can photoevaporate cores according to the models of Bertoldi (1989) and Bertoldi & McKee (1990).

Figure 3a shows the results of a test case for a Galactic protocluster ($4000 M_\odot$, $\Sigma = 1\ \mathrm{g\,cm^{-2}}$, model A in Fig. 1) interacting with the feedback from a single O star. As described in the caption, a clumpy, turbulent medium is much more capable of confining feedback. Such effects are undoubtedly important for confinement of ultra-compact HII regions, allowing them to be relatively long-lived.

Figure 3b shows the evolution of the size of the HII region for the three cases A, B and C shown in Fig. 1, which are relevant to typical Galactic massive clusters, Galactic Center clusters like the Arches, and super star clusters (SSCs). Note these models correspond to a constant volume density. A relatively slow star formation rate of $\eta = 30$ was adopted and material for new stars was taken from the innermost cores. Starburst99 models (Leitherer et al. 1999) were

used for the mean stellar properties. Again feedback effects are weaker than commonly supposed. In cases B and C pre-supernova feedback is confined for $\sim$3 Myr so the embedded phase lasts for at least this long. We predict that Wolf-Rayet spectral features should be seen in most young, optically visible SSCs. There are also implications for the numbers of observed embedded clusters (as probed in radio continuum, e.g. Johnson & Kobulnicky 2003) relative to young optically-revealed systems.

Even in the Galactic case (model A), which has an escape speed small compared to the ionized gas sound speed, ionization is confined for almost 2 Myr. This may be relevant to the Orion Nebula Cluster where stars still form in close proximity to O stars and where some cluster members are thought to have ages of ~ 2 Myr (Palla & Stahler 1999; Hoogerwerf, de Bruijne, & de Zeeuw 2001).

We emphasize that several important physical processes are not included in these models. Our treatment of stellar winds does not include protostellar MHD outflows or Wolf-Rayet winds, so wind feedback is underestimated. We assume a central point-like stellar distribution that enhances wind feedback because there are no wind-wind shocks. We ignore dynamical ejection of massive stars, which seems to be a relatively efficient: Hoogerwerf et al. (2001) argue that 4 out of 10 stars with $m_* > 10M_\odot$ have been ejected from the Orion Nebula Cluster. This obviously reduces the effectiveness of feedback. We assume star formation only begins once the clump is at the chosen density: in reality there will be a more gradual onset. We ignore further accretion to the clump from the surrounding GMC. The two component description of the gas is highly approximate.

The complexity of the star cluster formation process is daunting. The models we have developed are clearly a very crude first step. The reliability of such models can be established only with very detailed comparisons to observations of real clusters such as the Orion Nebula Cluster, R136 in 30 Doradus and nearby SSCs. For such comparisons, improved methods to date stars that are younger than a few Myr are needed.

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